Petrographic Analysis of a Columnar Section of the Bandelier Tuff, New Mexico

by

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ABSTRACT

The petrography of the Bandelier Tuff, Jemez Mountains, New Mexico is the result of two catastrophic eruptions producing two large, overlapping calderas. The study of vertical sections of the Bandelier Tuff has proven to be quite interesting in that variations in mineralogy may be indicative of conditions or zonations within the magma chamber prior to these eruptions. In this report, a composite columnar section was taken from Los Alamos Canyon east of Los Alamos, New Mexico. Twenty samples were taken, studied petrographically, and changes in mineralogy, textures and lithic fragment content were plotted against height in the section.

A marked increase in the number of phenocryst with depth in the chamber was represented in the petrography of the tuff. Alkali feldspar increased from 9.7 volume percent at the base of the section to 23.4 volume percent at the top showing an increase in temperature with depth in the chamber. An increase in the number of phenocrysts of hypersthene with height in the tuff also showed a tendency toward a more mafic composition of magma with depth in the chamber.

The most striking result of this report was the correlation between the number of lithic fragments within the tuff and the degree of welding. The inclusion of lithic fragments appears to retard welding of the tuff after emplacement causing the tuff to

be more densely welded in certain positions within the tuff where lithic fragments are less abundant. The results of this report prefer a binary cooling model for pyroclastic flows in which two components are responsible for the cooling rate, thence, welding of the Bandelier Tuff. From information contained within this report, the thermal properties of lithic fragments play a significant role in the degree of welding displayed by an ash-flow tuff.

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INTRODUCTION

The Bandelier Tuff is a succession of ash-flow tuffs and pumice beds that blanket the north, east and west portions of the Jemez Mountains, New Mexico. These tuffs are the result of a series of eruptive cycles that resulted in collapse of the volcano forming two large calderas. The tuffs are of rhyolitic composition and have been shown to display interesting chemical and petrologic variations within vertical sections (R. L. Smith, 1979).

The petrographic information contained within this report has been obtained from a composite column forming a vertical section from the east side of the Jemez Mountains. The column is composed of two sections due to the fact that no one outcrop exposes the entire thickness of the Bandelier Tuff. The column is roughly 200 feet thick and samples were taken at intervals of 5 to 10 feet. Sixteen of these samples are being used for this report.

The composite column was taken from the Pajarito Plateau (in the east flank of the Jemez). The plateau is about 60 miles north of Albuquerque and 25 miles northeast of Santa Fe in Sandoval County, New Mexico (see Figure 1). The exposures for the column are in Los Alamos Canyon near the junction of State Route 4 to Los Alamos and State Route 4 to White Rock (there is no misprint here, SR4 forms a loop around the east and southeast of the Jemez and joins itself at the end of Los Alamos Canyon). For those who wish a more precise location, it is longitude 106° 12' W and latitude 35° 53' N (see Figure 2).

This report deals with applying techniques of petrography and petrology in order to determine mechanisms of eruption that produced the Bandelier. I will present the results of petrographic investigation of this vertical section of rocks through the thickness of the Bandelier. The investigation was designed to describe the mineralogy of individual specimens and to describe observed variations in mineralogy throughout the section. The variations in mineralogy and petrology will then be tabulated in the report and used to draw possible conclusions as to mechanisms for the Bandelier-producing eruptions.

GEOLOGIC SETTING

The Bandelier in the Pajarito Plateau overlies tertiary lake sediments of the Santa Fe group and basalts of the Cerros del Rio. The lower member (the Otowi member) varies in thickness reflecting pre-eruptive topography and pre-upper Bandelier erosion. The upper member (the Tshirege member) also varies in thickness for the same reason. At the location of study, the Otowi member is roughly 50 feet thick and the Tshirege member roughly 150 feet thick. The two members together blanket roughly 500 square miles of land. The Otowi (lower) member, before being extensively eroded, covered approximately 830 square miles in a generally south and southwest direction from the caldera whereas the Tshirege member also covered roughly the same area in a predominantly northwest direction from the caldera (G. Heiken, personal communication, 1985).

The two members of the Bandelier were produced in two catastophic eruptions that resulted in the formation of two large, overlapping calderas: the Valles and Toledo Calderas (see Figure 2). The eruptions have been dated by means of potassium-argon methods at 1.0 and 1.4 million years ago (Doell, et al., 1968). The Otowi member corresponds to the collapse of the Toledo; the Tshirege corresponds to the collapse of the Valles Caldera. Within each member, a varying number of individual and distinct flow-units have been described. Each of these is the deposit of a single pyroclastic flow (Suthren and Furnes, 1980). In the area of study for this paper, four of these flow-units are present; one in the Otowi member, three in the Tshirege (Crowe, et al., 1978). Each member, with its flow-units, represents a full cycle through an eruptive event. These two cycles have been stated to bring to an end a long history of basaltic and andesitic to quartz-latitic and rhyolitic volcanism in the Jemez Mountains (Smith and Bailey, 1966).

STRATIGRAPHY

The Bandelier in the Pajarito Plateau overlies tertiary lacustrine sandstones and shales of the Santa Fe Group and basalts of the Cerros Del Rio (see Figure 3). An erosional unconformity separates the lower Bandelier from the units below. The base of the lower Bandelier is composed of a thick pumice bed that resulted from a Plinean eruption which preceded the pyroclastic flows that produced the flow-units of the Otowi member. The lower Bandelier in its entirety consists of two flow units, each of which represents a single pyroclastic flow. The upper Bandelier consists of three flow units and is defined at the base by a thin plinean ash-fall deposit. Again, preceding this member, is an erosional unconformity that has erased parts of, and in some places all, of the Otowi member.

Within the two members of the Bandelier Tuff at the area of study, four cooling units are apparent; three of these belong to the upper member. Within the flow units, macroscopic variations are quite visible. Variations in the degree of welding, changes in the number and size of pumice clasts, and changes in color were noted as the section was traversed (see Figure 3). Macroscopic and megascopic features that were noted in the section are: columnar jointing, surge deposits, imbrication of pumice clasts and bedding within the tuff. Because only one flow-unit of the Otowi member is present at the location of this study, only the characteristics of the Tshirege member will be presented herein.

The most striking characteristic of the Bandelier Tuff is columnar jointing. It is this feature along with the distinctive pink and white coloring that makes the Bandelier Tuff easy to identify. The columns vary in width from about a meter in diameter to more than three meters in diameter with outside angles ranging from <90° to about 120°. As the tuff has been eroded, the weathered material has broken away in large blocks leaving behind large vertical cliffs. It is this feature that made sample collection very easy (see Figure 4).

Variation in clast size within each cooling unit was noted and one appeared to be normally graded whereas the others were inversely graded. The grain size variations consisted of variations in the size of both pumice clasts and lithic fragments. The two units that displayed inverse grading, Units I and II, eventually graded into a pumice swarm. The third unit, Unit III of Figure 3 , showed normal grading, decreasing in both size and number of pumice clasts and lithic fragments. This suggests that during the events that produced Units I and II the eruptive cycle began with a pelean-type eruption and tended toward and eventually ended in a plinean-type eruption. In Unit III, the cycle was just the reverse: with the eruptive cycle beginning in a somewhat plinean-type eruption and ending with a large pyroclastic flow (see Figure 5).

Within each unit, the degree of welding also varies greatly. The degree of welding within ash-flow tuffs has been related to the amount of lithic fragments included within the formaion (Eichelberger and Koch, 1979). In that report, the conclusion was drawn that lithic content of more than 10% was enough to prevent welding within a tuff. Variations between 0 and 10% lithic content had direct influence upon the degree of welding. In the Tshirege Unit I of this report, welding was substantially low. The reason for this may be due to a higher rate of scour during the initial stages of eruption. The base of th unit was not well welded and the degree of welding increased steadily toward the top. The base of Unit II was well marked by a sudden change in the degree of welding. Moving upward through this unit, the degree of welding decreased in the middle and changed little toward the top of the unit. Unit III was the most densely welded of the three and showed interesting variations. The relative amount of welding was measured in the field by observing the relative amount of consolidation each unit displayed. The degree welding has also been measured as a function of porosity and will be discussed later in this report.

Pyroclastic surge deposits, common to most ash-flow tuffs, are small (less than 20 inches in thickness) features, and are the result of a low density, high velocity flow that precedes the much higher density pyroclastic flow during a single ash-flow event (Sheridan, 1979). Normally, they appear at the base of a flow unit, making a sharp contact with the underlying unit. Only one of these surge deposits was found in the traverse made for this study. This deposit defined the contact between flow-units I and II (see Figure 6). The thickness of the deposit varied between 4 and 8 inches and extended throughout the area of study. The deposit is composed of medium to coarse sand-sized pumice fragments with very few lithic fragments. The structures within be more densely welded in certain positions within the tuff where lithic fragments are less abundant. The results of this report prefer a binary cooling model for pyroclastic flows in which two components are responsible for the cooling rate, thence, welding of the Bandelier Tuff. From information contained within this report, the thermal properties of lithic fragments play a significant role in the degree of welding displayed by an ash-flow tuff.

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Otowi member and another pumice layer (Tsankawi pumice bed) marked te base of the Tshirege (see Figure 3).

The formation has been studied by workers from several different subdisciplines of geology. Robert L. Smith has studied the formation for mineralogy and chemistry with respect to zonal variations within ash-flow tuffs (1960, 1966) and also in comparison to other welded and non-welded tuffs around the world (1979). Wolfgang E. Elston and Eugene I. Smith dealt with petrographic structures within the Bandelier using these to detrmine flow directions of ignimbrites. The age of the tuff has been defined by means of K/Ar dating (as stated earlier) by Doell and Dalrymple (1968). The Bandelier is now being extensively studied for use as a potential hot-dry rock (see Appendix) resource and as a depository for hazardous waste by the Los Alamos National Laboratory (Crowe, et al., 1978, and also G. Heiken, personal communication).

PETROGRAPHY

At first glance, the mineralogy of this formation appears to be monotonous and simple: A groundmass of glass shards, phenocrysts of potassium feldspar and amphibole, minor pyroxenes and opaques; and secondary biotite, chlorite, and iron oxide. Upon closer examination, the mineralogy varies considerably and enough to illustrate significant magmatic trends. In this section, I will present the changes in petrography within the composite column taken from the Pajarito Plateau. Volume percents have been calculated by means of point-counting of phenocrysts in each sample. Volume percents were then plotted against position within the column. The results have been tabulated in the text and figures to follow. Data for this section has been taken from single sections of bulk rock. Though the data may not be totally representative, changes are sufficiently large to be significant.

Bulk occurrences have been tabulated versus position in the composite column in Table 1. The occurrence of lithic fragments, opaque minerals, orthoclase, amphibole, biotite, quartz, pumice clasts, plagioclase, and pyroxenes were plotted in a simple graph to show visually mineral content versus position in the vertical column. Notice that bulk occurrences do not change significantly wih height.

Lithic Fragments

Lithic fragments within the tuff are of various compositions and range sizes. The majority are of basaltic composition and range in size from less than .25 cm to greater than several centimeters (see Figure 7). The basaltic fragments have been derived from basalts that lined the walls of the vent prior to the caldera-forming eruptions. They were apparently torn from the sides of the vent as the eruptive column scoured and widened the vent during the eruptions. Other lithic fragments of sandstone and siltstone composition are apparently derived from basement rocks below the Jemez volcanic pile. The great number of xenoliths included in the Bandelier has been attributed to the flaring of the vent and to the slumping of large blocks of the vent walls and subsequent fracturing and inclusion of those blocks in the eruptive column (Eichelberger and Koch, 1979; Smith and Bailey, 1966).

Welding of the Bandelier Tuff has been related to the weight percent of lithic fragments included within the tuff (Eichelberger and Koch, 1979). Welding has been measured as a function of porosity, that is to say that the more porous the tuff is, the lower the degree of welding (Eichelberger and Koch, 1979; Smith and Bailey, 1966). In previous reports, the degree of welding has been related to the temperature of emplacement and that variations in emplacement temperatures will result in varying degrees of welding. However, Eichelberger and Koch (1979) demonstrated that a xenolith content of greater than 10 wt. percent will absorb sufficient heat to inhibit welding.

In a given flow-unit (cooling unit in this case, see Appendix) that is emplaced relatively instantaneously, one would expect that cooling would take place from the top of the unit downward and from the base of the unit upward. Assuming that the unt contained more or less homogenous material, or at a uniform temperature, the least welded portions would be at the top and base f the unit, leaving the highest degree of welding in the middle of the unit.

In the case of the Bandelier Tuff, welding is obviously not a function of position within the cooling unit. In a macroscopic sense, welding appears to be almost random; in some cases decreasing steadily toward the top of a given cooling unit or increasing steadily toward the top or varying degree several times within a single unit. After closer examination the fluctuations in the degree of welding are revealed to be a function of xenolith content. For example, flow-unit I of this report shows a steady increase in welding from base toward the top of the unit. At the base of this unit is a pumice swarm with a relatively high number of lithic fragments. Moving upward in the unit, the number of lithics decreases significantly toward the top. As the number of xenoliths decreases, the degree of welding increases proportionately. In Unit III, this can be seen in the volume percents of lithic fragments contained within samples 2-31, 2-32, 2-33, 2-34 (see Figure 8). In these samples, the volume percent varies from 0.4 volume percent the base to 2.6 volume percent apparently causing increases and decreases in the degree of welding with height in the unit.

If we pursue the question as to the cause of concentration of lithic fragments at certain locations within the column, the answer may be due to the amount of scouring that takes place within the vent during the eruptive blast. The least welded of all of the units of the upper Bendelier Tuff, is Unit I. The overall degree of welding appears to increase in Units II and III. If we trace this to activity within the vent at the time of the eruption, one might conclude that the amount of flaring of the vent taking place early in the eruptive cycle was greater than the amount of flaring in later stages of the eruptive cycle.

Preliminary Mineralogy

The mineral association of the Bandelier Tuff is relatively simple. The majority of phenocrysts are alkali feldspars and pyroxenes with a few small phenocrysts of olivine. The groundmass is composed of glass shards, chalcedony, biotite, fe-opaques and fe-oxides. The Tuff is relatively young (1.0 and 1.1 million years), therefore the mineralogy is well preserved; the glass shards have devitrified only a small degree. Almost all phenocrysts show good fracturing due to the velocity of the ash-flows and the percussion between individual grains during transport (see Figure 9). The modal proportions of the phenocrysts is indicative of rhyolite.

The average grain size of the phenocrysts is about 1.5 mm diameter. The most abundant and largest phenocrysts are alkali feldspar. The composition of the feldspars are orthoclase and sandine. Because these two minerals are only distinguishable under a microscope by their optic angle (2V), they will be grouped together as alkali feldspars in this report. The pyroxene in this report is hypersthene and the olivine is fayalite. Most of the phenocrysts are anhedral to subhedral. In many cases the phenocrysts are fractured; again, this is due to impact within the flow during transport and in the neck/vent system prior to effusion.

Secondary minerals occur within the Bandelier Tuff as weathering products of other minerals. They occupy interstices between grains and the groundmass or between individual phenocrysts, or as in the case of chalcedony, occur as infilling within the vesicles as a result of devitrification of the glass shards. Biotite occurs as an alteration product of hypersthene and hornblende. Chlorite appears as the weathering product of olivine. Both chlorite and biotite are found in association with the minerals or phenocrysts from which they were derived. The occurrence of secondary minerals appears to be a direct function of the degree of weathering and porosity of the individual unit. The more porous units (also least welded) showed the greatest effect of weathering. This appears to be a function of the amount of groundwater that the unit is able to transmit. The minerals most quickly attacked were the ironoxides and olivine.

Textures

The basic texture of the Bandelier Tuff is (almost without saying) porphyritic (see Figure 10). Large phenocrysts surrounded by a microcrystalline framework of glass, glass shards, and iron oxides. The texture, at a quick glance, seems quite trivial, but upon closer examination the texture does lend itself to some discussion. For example, evidence is contained within the texture that lead to mechanisms of eruption, emplacement temperature and the direction of flow of the moving ash cloud (Smith, 1960; Eichelberger and Koch, 1979; Elston and Smith, 1970).

Resorbtion rims on individual phenocrysts may be due to an increase in pressure and temperature conditions within the magma body just prior to eruption. The increase P/T conditions may be due either to the introduction of a new, hotter magma into the bottom of the magma chamber or convection within the magma chamber carrying a cooler magma downward into a higher P/T region within the chamber or crystal settling. Whichever one of these three occurred, as the molten material surrounding the phenocrysts is heated, the crystals begin to resorb back into the magma. If the material is erupted before complete resorbtion can take place, the crystals are left with a periferal rim that is either of a different composition than that of the middle of the phenocryst or with a rim that appears as if the crystal has partially "decayed" (see Figure 11).

The bending and recrystallization of some phenocrysts may lend itself to the temperatures of a flow unit at the time of emplacement. Low temperature minerals such as biotite may be bent and recrystallized in a manner that suggests that the emplacement temperatures were very near or just above the melting point of the individual mineral. The occurrence of these minerals is usually in association with xenoliths of basement material or from the inclusion of fragments from lavas from around the volcanic neck (Eichelberger and Koch, 1979). If enough samples were to be taken (a project which is beyond the scope of this report), the degree to which deformation within crystals has taken place might fix an emplacement temperature for ignimbrite flow unit.

Orientation of glass shards and "shadows" from phenocrysts along with other features have been used to determine azimuths of flow direction for pyroclastic flows (Elston and Smith, 1970). Fork-shaped glass shards tend to orient themselves in a flow-parallel direction with their long end pointing downstream at the time of emplacement of the Tuff (see Figure 12). In addition to this, the blocking-effect of phenocrysts at the time of emplacement tends to leave a shadow on the downstream side of the phenocryst. Tabulation of these features over a broad area can produce an approximate flow direction in much the same way as paleocurrent studies are commonly done in the realm of sedimentology.

Trends

If we assume, in fact, that the Bandelier Tuff represents the reverse of what was present within the magma chamber prior to the eruptive cycle, then the stratigraphy of the tuff will reflect trends or zonations within the magma chamber only in reverse order. That is to say that what is at the top of the Bandelier was at one time further down within the magma chamber and what is at the bottom will, of course, reflect what was at the top of the magma chamber. Therefore, moving upward in the stratigraphic sequence of the Bandelier Tuff we see the tapping of the magma chamber from top to bottom.

Trends were observed in the volume percent, size and composition of phenocrysts and in the volume percent of vesicles versus lithic fragments. The reason for paying special attention to these two trends is as follows: The trends observed within the tuff of phenocrysts should represent gradients and zonations within the magma chamber prior to eruption; and trends in the number of vesicles represents the amount of welding that occurred in situ after the tuff had been laid down and begun to cool.

Information for this part of the report was done by tabulation by means of point-counting on the thin sections of bulk rock. The volume percents were calculated from the point-count information and then plotted against height in Table 2. Biotite and pumice clasts were included together and into groundmass. Reasons for doing this are: (1) Biotite occurs only as a weathering product of the tuff, and (2) the pumice clasts were virtually all glass and contained no phenocrysts, therefore they had no significant effect on mineralogic or textural trends with height within the vertical column. Vesicles and lithic fragments were kept as separate categories because they show the behavior of the rock unit after it had been emplaced. They had no direct bearing on the mineralogic trends of the tuff, but the trends that these two components show are quite interesting.

The most obvious trend within this vertical column is the variation from base to top of the volume percent of alkali feldspar. Moving from the base toward the top, both the number and size of feldspars increase. Figure 8 shows volume percents of alkali feldspars plotted against height within the section. The volume percent roughly doubles from the base at 10.4 volume percent to 23.4 volume percent at the top of the unit. This seems to represent the tapping of a chamber that becomes more phenocryst-rich with depth. In addition to this, the composition of the alkali feldspars varies with height. At the base of the section, the composition of the alkali feldspars are orthoclase and sanidine. Moving toward the top of the unit, orthoclase is replaced by anorthoclase. This suggests the tapping of a chamber whose magma becomes more sodic with depth. Another trend which is not as apparent as the above, but can be seen in Figure 13, is the variation in volume percent of hypersthene. Moving upward in the column, the volume percent goes from 0.4 volume percent at the base to 2.2 volume percent at the top of the section. These trends indicate that zonation within the magma chamber was both thermally controlled and compositionally controlled. The chamber appears to become more sodic and more mafic with depth. The thermal gradient seems almost elementary becoming warmer with depth.

The other striking and most relevant trend is the variation of vesicles with height in the column and the variation of the number of lithic fragments within the column. The variation in the volume percent of lithic fragments seems almost sporadic with height. If we compare this with the number of vesicles, a trend appears that seems to correlate the two (see Figure 14). We will assume here that the number of vesicles represents the degree of welding which has taken place after emplacement of each flow-unit. The degree of welding seems to correspond with the number of lithic fragments within this tuff. If we concentrate on samples 2-31, 2-32, 2-33, 2-34, which were taken from flow-unit III of the report, we can see that as the relative number of lithic fragments increases and decreases, so do the number of vesicles. If we assume that if more vesicles are present in a particular position within the tuff the less welded that portion of the tuff then it becomes apparent that the amount of lithic fragments caught within the tuff controls the degree of welding. that is to say that the more lithic fragments that are present at any location within the section, the less welded the tuff will be.

DISCUSSION

The main drive behind this study was to search for evidence for the mechanisms of eruption and for zonation within the magma body below the Jemez volcanic pile. Clues to these questions were found in the textures, bulk mineralogy, and trends in mineralogy within a vertical section of the Bandelier Tuff. Some assumptions have been made in analyzing the data acquired for this report. These are: (1) the vertical succession of ash-flows within the Bandelier Tuff were laid down in a "layer-cake" fashion and stratigraphically represent the inverse of vertical zonation within the magma body at the time of eruption. (2) No mixing, crystal settling, or fractionation of magma within the chamber occurred between eruption of successive ash-flows, and (3) all assimilation and resorbtion of phenocrysts had taken place prior to the eruption. That is to say that no resorbtion took place during cooling of the flow unit. With these assumptions, the vertical stratigraphy should correlate with verticl conditions within the magma chamber, only in reverse order. These appear to be justifiable assumptions because the successive ash flows were laid down within a relatively short time period. The ages for the flow units of the Tsirege member are given as 1.09 Ma, 1.06 Ma, and 1.02 Ma (Doell, et al., 1968).

The time period between the individual eruptive events are not short enough to be taken solely as the cause for prevention of major differentiation of magma within a chamber. Some systems have, for example, exhibited fractionation in eruptions over a 200-year period (M. Barton, personal communication, 1985). Chemical studies of the Bandelier Tuff in vertical sections have shown relatively little fractionation within the magma chamber during the period in which the Bandelier Tuff was produced (Smith, 1979; Sheridan, 1979).

Eruptive Mechanisms

The mineralogy of the Bandelier Tuff lends itself to some discussion of mechanisms of eruption for these two caldera-forming events. Of the possible mechanisms for eruption, it may be possible to determine the cause of the eruption by a process of elimination by examining the model mineralogy of phenocrysts within the tuff. Possible mechanisms of eruption are: (1) the interaction of groundwater with magma within the chamber causing a phreatomagmatic eruption; or (2) the exsolution of volatiles from the magma within the chamber; or (3) the introduction of a hotter, more primitive, magma into the bottom of the chamber. In determining which of these factors was the primary cause for the eruption, we must compare the mineralogy of the tuff with the mineralogy that would be expected from each of these mechanisms.

In the case of both the interaction of groundwater with magma in a phreatomagmatic eruption and the evolution of volatiles from a magma, we would expect to find a large number of hydrous minerals included as phenocrysts within the modal mineralogy of the tuff. As can be seen from data stated previously in this report, there is a strong underrepresentation of these types of minerals in the phenocryst mineralogy. Minerals such as biotite, hornblende, and other amphiboles do not occur in any significant abundance throughout the sections described for this report. This suggests that preeruptive water did not play a significant role during the evolution of the magma.

Evidence for a phreatomagmatic interaction would be represented by cross bedding within the tuff. It has been demonstrated that ash flow tuffs which are the result of phreatomagmatic eruptions show abundant cross bedding (Suthren and Furnes, 1980). The only cross bedding that has been observed in the Bandelier Tuff is in the surge deposit between Tshirege Units I and II and in the Guaje Pumice Bed. The surge deposit between Tshirege Units I and II is the result of a ground-surge which occurred beneath the pyroclastic flow that produced Unit II; this type of depsits display antidune structures regardless of the mechanism of the eruption. Other evidence for the interaction of pre-eruptive water with the magma would be the abundace of vesicles represented by glass shards in the tuff. This does not prove or disprove the idea of the outgassing of volatiles from the magma as a major factor in causing the eruption; more evidence is necessary to draw a conclusion.

Evidence was found, though, for the interaction of a new, hotter magma with the more evolved magma within the magma chamber prior to eruption. The relative lack of hydrous and low temperature minerals suggests that the magma had not evolved to the extent that these minerals would be present. The strongest evidence for the introduction of a new magma are the resorbtion features present on phenocrysts of alkali feldspar. It was noted that the abundance of resorbed phenocrysts increased with height in the vertical column. The resorbtion features suggest thermal disequillibrium within the magma after it had begun to evolve. The resorbtion of these phenocrysts suggests that the liquid surrounding the phenocrysts had heated up prior to the eruption and the alkali feldspars were being re-included into the magma.

The strongest evidence for the introduction of a new magma into the chamber would have been the evidence for a more primary maga included within the rhyolites of the Bandelier Tuff. Evidence for this would be xenoliths included in the tuff which could be proven to have been liquid at the time of eruption. This would have been represented by widulose, irregular edges of the xenoliths proving that two compositions of magma were present in liquid form at the same time within the chamber. Other evidence would be present in chemical studies of the tuff in that two distinct compositions would arise on a normative diagram showing that two compositions of magma are present in the Bandelier Tuff. This leaves an area of study of the Bandelier Tuff that is open to future study.

Zonation

From the data presented in this report, evidence is present for zonation within the magma body prior to the eruptive sequence. Zonations appear in both the number and composition of phenocrysts contained within the Bandelier Tuff. Trends in phenocryst content suggest thermal gradients, and it follows that if a thermal gradient is present then a compositional gradient will also be present. In general, the trend within the magma body was toward higher temperature and decreased silica content with depth.

Phenocryst content within the magma appears to increase strongly with depth. As can be seen in Figure 8, the volume percent of phenocrysts, both total phenocrysts and alkali feldspar increases steadily with height in the tuff. If we correlate this with conditions within the magma body prior to eruption, this increase represents a relative increase in temperature with depth in the chamber. This follows what one would expect in a thermally zoned chamber in which the margins of the chamber are cooler than the more central portions. The increase in vertical concentrations within the Bendelier Tuff, here represent the tapping of a chamber that becomes more phenocryst rich with depth and shows a tendency toward equilibrium cooling within the chamber with depth exhibited by the lack of zoning on phenocrysts.

One might argue, here, that the increase in phenocryst content is evidence for crystal settling within the magma chamber. A simple model would be that as the crystals form, their density carries them down within the chamber and concentrates them with depth. Strong evidence has been presented against crystal settling in recent years (Smith, 1979; Barton and Huijsmans, 1985). Reasons behind this train of thought include the high viscosity of silica-rich magmas and the non-newtonian liquid behavior of magma within the chamber. Processes that may dominate to produce this zonation are convection-driven thermogravitational diffusion and crystal fractionation by preferential nucleation at the cool contacts of the magma body and the wall rock (Smith, 1979; Hildreth, 1979).

The other important feature that was revealed when compiling te data for this report was the appearance of anorthoclase toward the top of the section in replacement of orthoclase. This holds with R. L. Smith's model for a compositionally zoned chamber showing a tendency of the magma to become more sodic with depth. The appearance of anorthoclase is not gradual but is rather sudden appearing only in Unit III of this report. The cause for the sudden appearance of anorthoclase is probably due to a transition within the chamber due to a change from assimilation-dominated processes to fractionation-dominated processes in a downward fashion within the chamber.

Welding

The most interesting characteristic that was displayed by the petrography of the Bandelier Tuff is the relationship between the degree of welding and the amount of lithic fragments within the tuff. Welding is directly related to the cooling pattern of the material after it had been laid down. It has generally been thought that unitary cooling takes place within pyroclastic flows thereby leaving behind a unit which is least welded at the margins and more densely welded in the center (Smith, 1960a). Evidence was found in this study that suggests that lithic fragments may play an important role in the cooling pattern of welded tuffs.

If we assume a unitary cooling pattern for the Bandelier Tuff, we would find within the flow units characteristics like those previously stated. The trend that was found in the study for this report shows this not to be the case. The factor that seems to dominate is the volume percent of lithic fragments included within any given flow-unit. We might assume a binary cooling pattern for the Bandelier Tuff in that the magmatic material was emplaced at a much higher temperature than the country rock that it included during eruption. it appears as though enough heat was absorbed by the xenoliths that welding of the tuff was prohibited or inhibited at certain locations within the vertical section. The binary cooling process would be the emplacement of material that is not at a relatively uniform temperature but rather the emplacement of a high temperature materil that has with it a cooler material that has the ability to absorb heat after emplacement has occurred. This study supports the model proposed by Eichelberger and Koch (1978) as opposed to that of Smith (1960a).

CONCLUSION

The information contained herewith suggests gradients, both thermal and compositional, within the magma chamber prior to the eruptive events that produced the Bandelier Tuff. Trends in mineralogy appear that suggest an increase in temperature toward the center of the chamber and a tendency toward a more mafic composition of the magma in a downward fashion within the chamber. Also, the appearance of anorthoclase in replacement of orthoclase suggests a compositional gradient within the chamber that becomes more potassic with depth. These zonations substantiate the models proposed by R. L. Smith (1960b, 1966, 1979) on the origins of zonations that appear within welded ash-flows.

The other result of this report suggests a correlation between the number of lithic fragments at certain positions within the tuff and the degree of welding at the same location. This appears to substantiate a model proposed by Eichelberger and Koch (1979) in which the ability of lithic fragments to absorb heat inhibits or prevents the welding of ash-flow tuffs. The results of this report showed an inverse proportionality between the number of lithic fragments and the degree of welding at given positions within the vertical section.

Much work still has to be done on pyroclastic flows in both the chemical sense and the physical sense. Clues to chemical properties within magma bodies are present within these deposits and are still poorly understood and understudied. Also, the apparent ability of pyroclastic flows to leave continuous and planar deposits on high angle slopes and their ability to surmount very large topographic barriers is a realm which is not fully understood (Sheridan, 1979). Much work has been done since th pioneering works of R. L. Smith (1960a), but much work still needs to be done in this realm of the science of geology.

APPENDIX

The Bandelier Tuff as a hot-dry rock resource. The Bandelier Tuff not only blankets the flanks of the Jemez Mountains, but also fills the Valles Caldera to a depth of about 5000 feet. There it rests upon still hot rocks from post caldera eruptive sequences. The Los Alamos Scientific Laboratory is presently exploring this region in the Valles Caldera for use of the Bandelier Tuff as a reservoir rock in order to transmit water from one well to another while it is being heated from the rocks below. The high porosity of the Bandelier Tuff suggests a potential for this sort of resource (G. Heiken, personal communication, 1985).

Flow-units versus cooling units of ash-flow tuffs. By definition, a flow-unit is the deposit left behind from a single pyroclastic flow and a cooling-unit is a layer of pyroclastic material that shows unitary cooling from the margins inward (Christiansen, 1979). A cooling unit may or may not contain more than one flow-unit. In the case of the Bandelier Tuff, however, the flow-units correspond to cooling units in that each flow-unit cooled separately from those above or below it. The two terms may be and will be used interchangeably.

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LIST OF FIGURES

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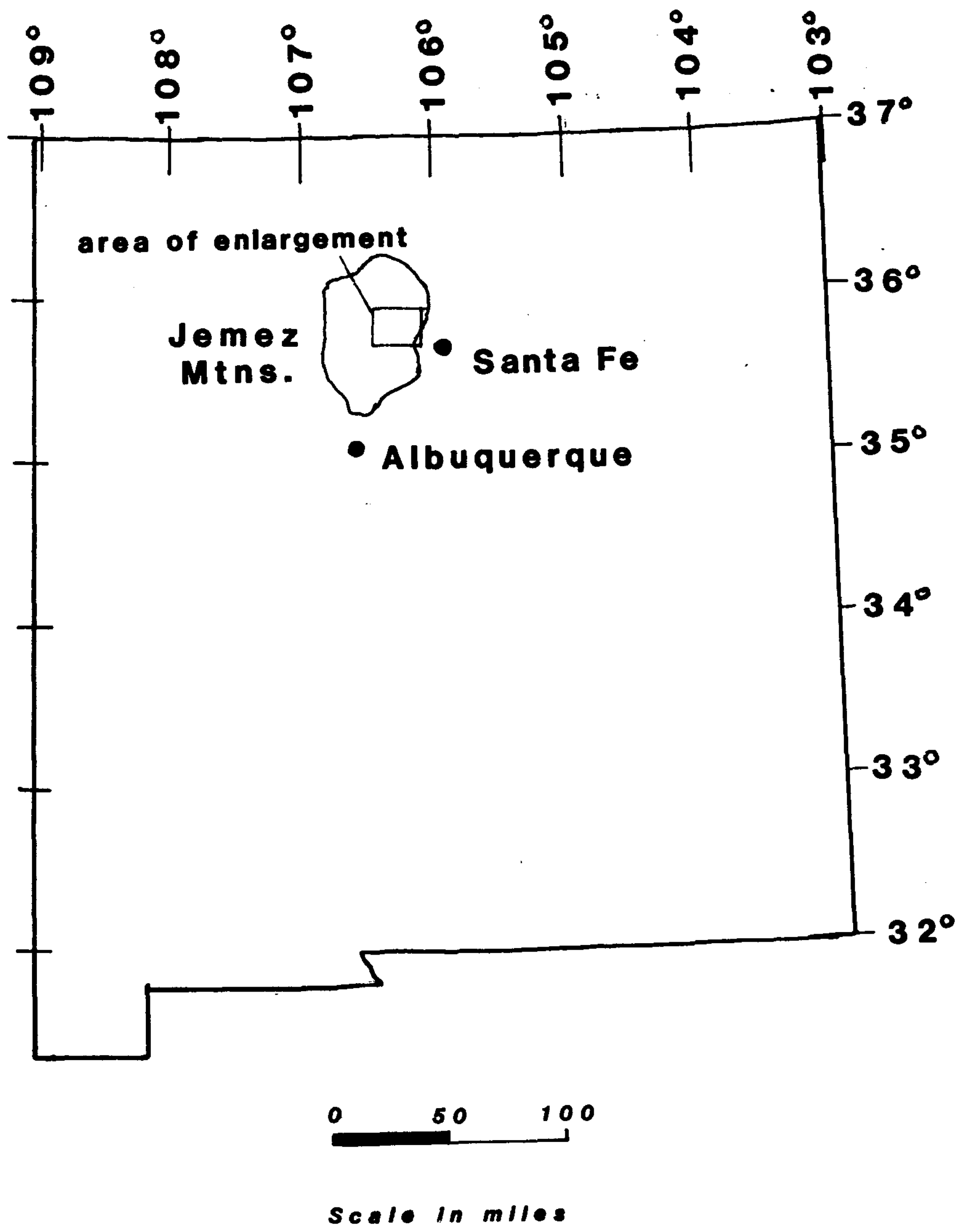

109°
108°
107°
106°
105°
104°
103°
37°
36°
35°
34°
33°
32°
area of enlargement
Jemez
Mtns.
Santa Fe
Albuquerque
0
50
100
Scale in miles

Figure 1

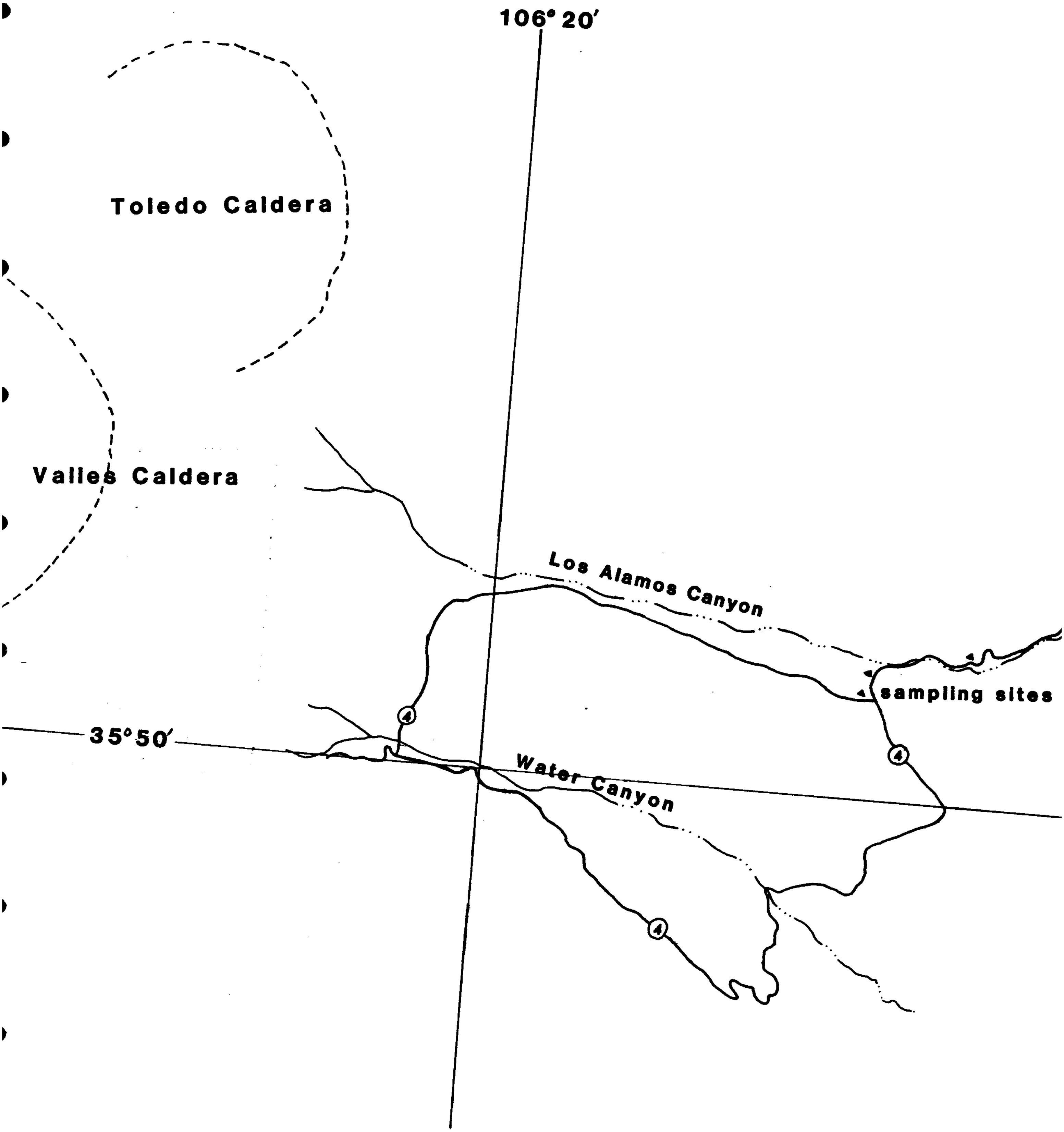
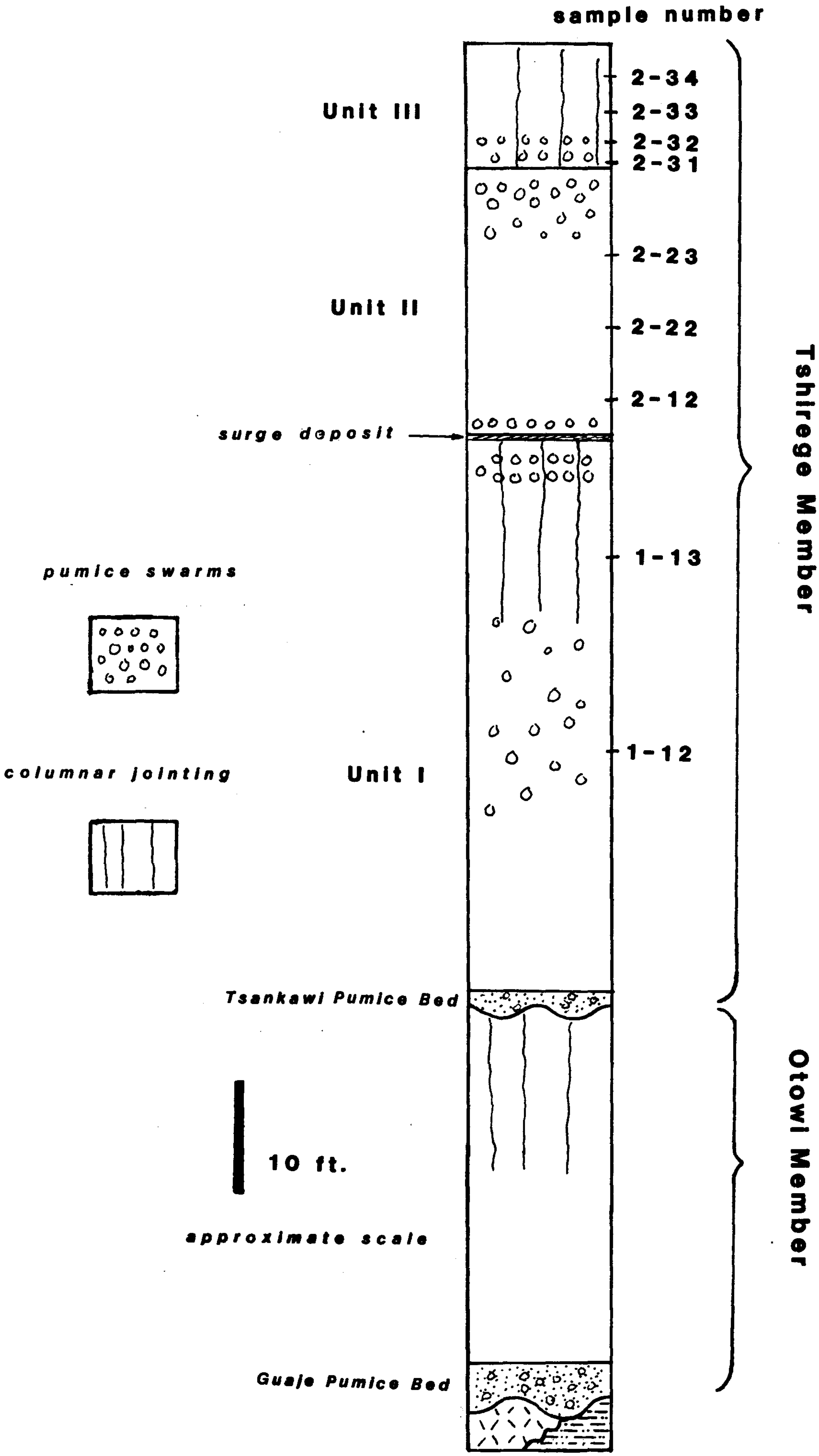
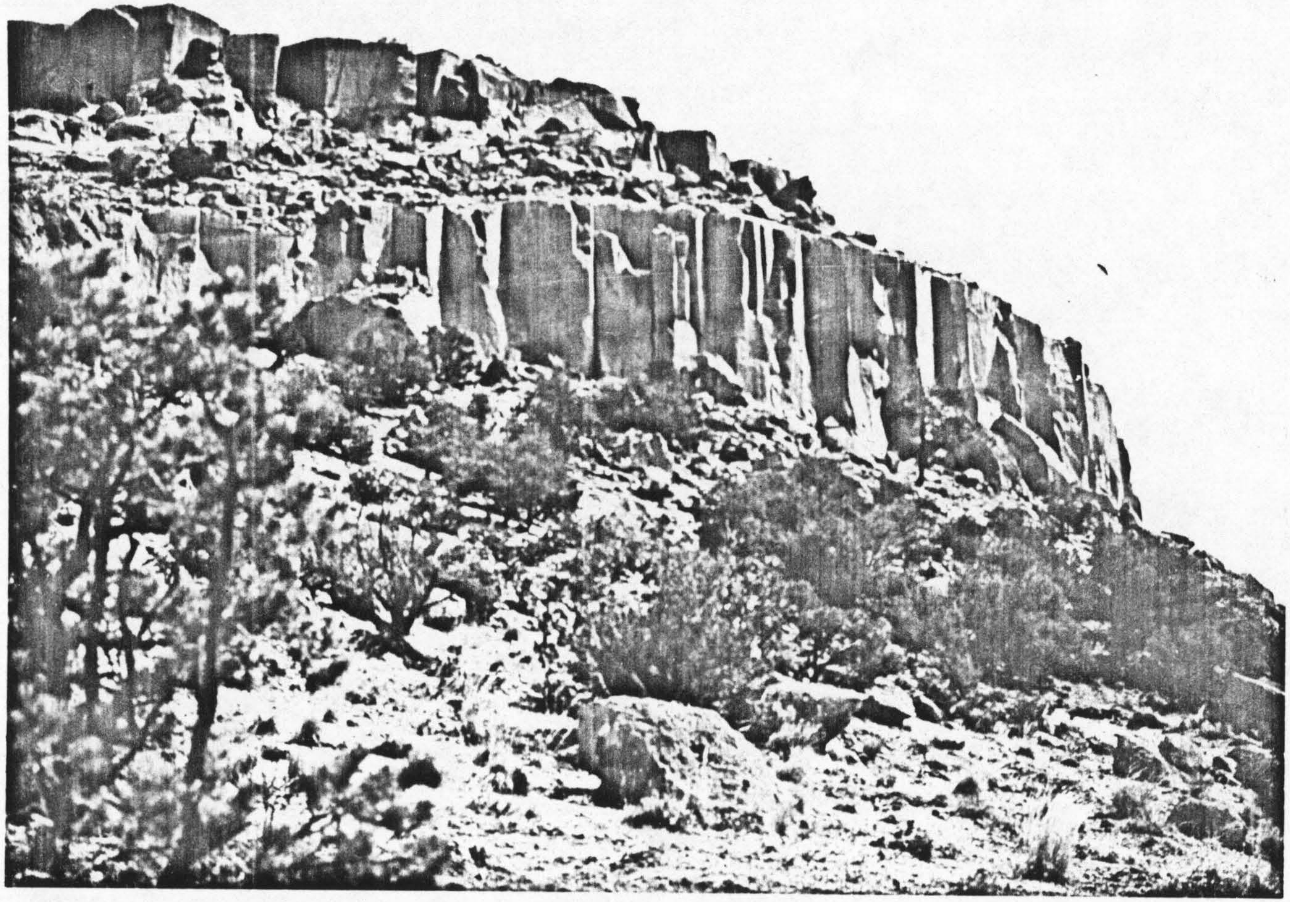

106° 20′
Toledo Caldera
Valles Caldera
Los Alamos Canyon
sampling sites
35°50′
Water Canyon
4
4
4

Figure 2



sample number
Unit III
2-34
2-33
2-32
2-31
Unit II
2-23
2-22
2-12
surge deposit
Tshirege Member
1-13
pumice swarms
Unit I
1-12
columnar jointing
Tsankawi Pumice Bed
Otowi Member
10 ft.
approximate scale
Guaje Pumice Bed

Figure 3



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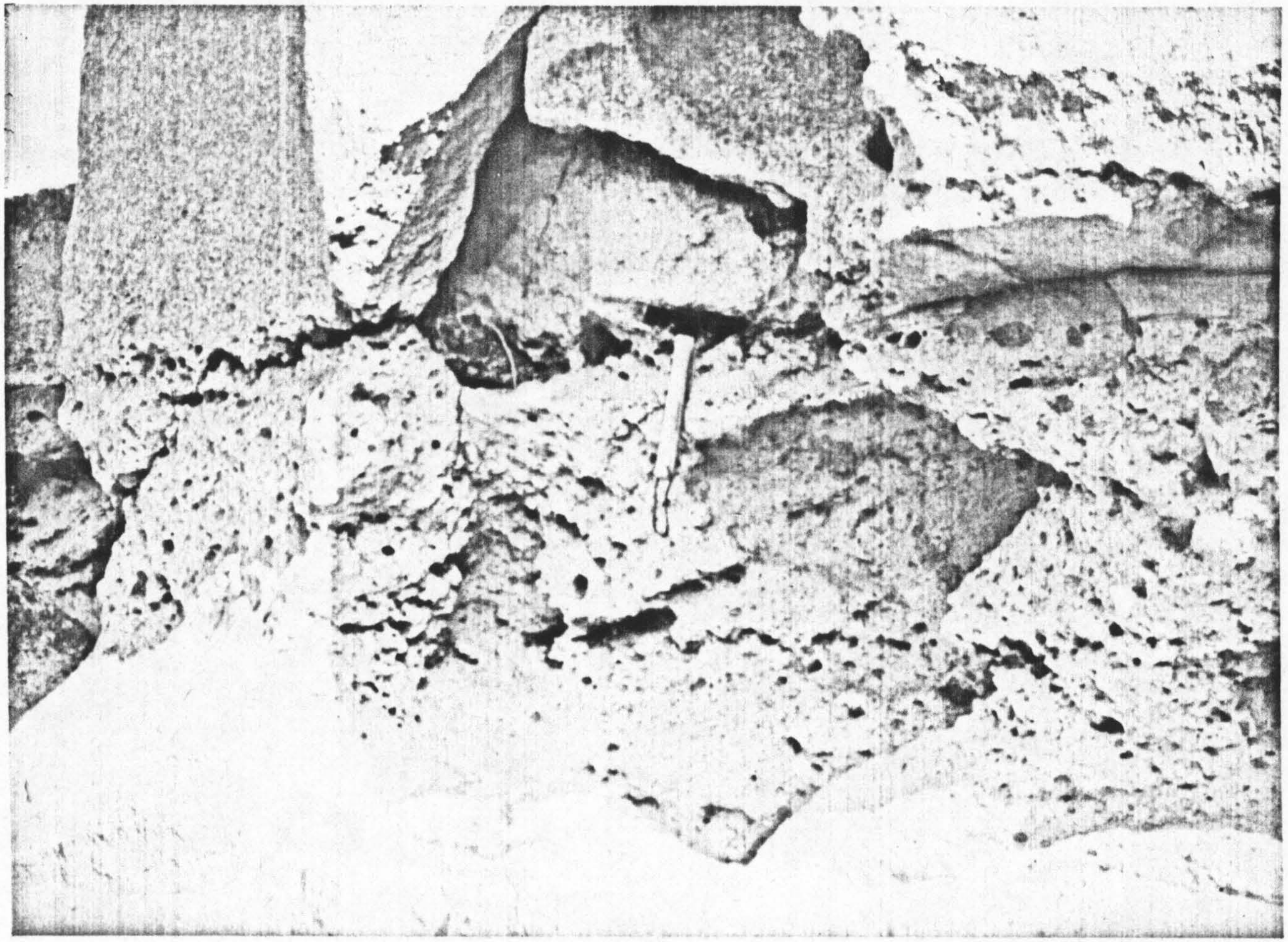

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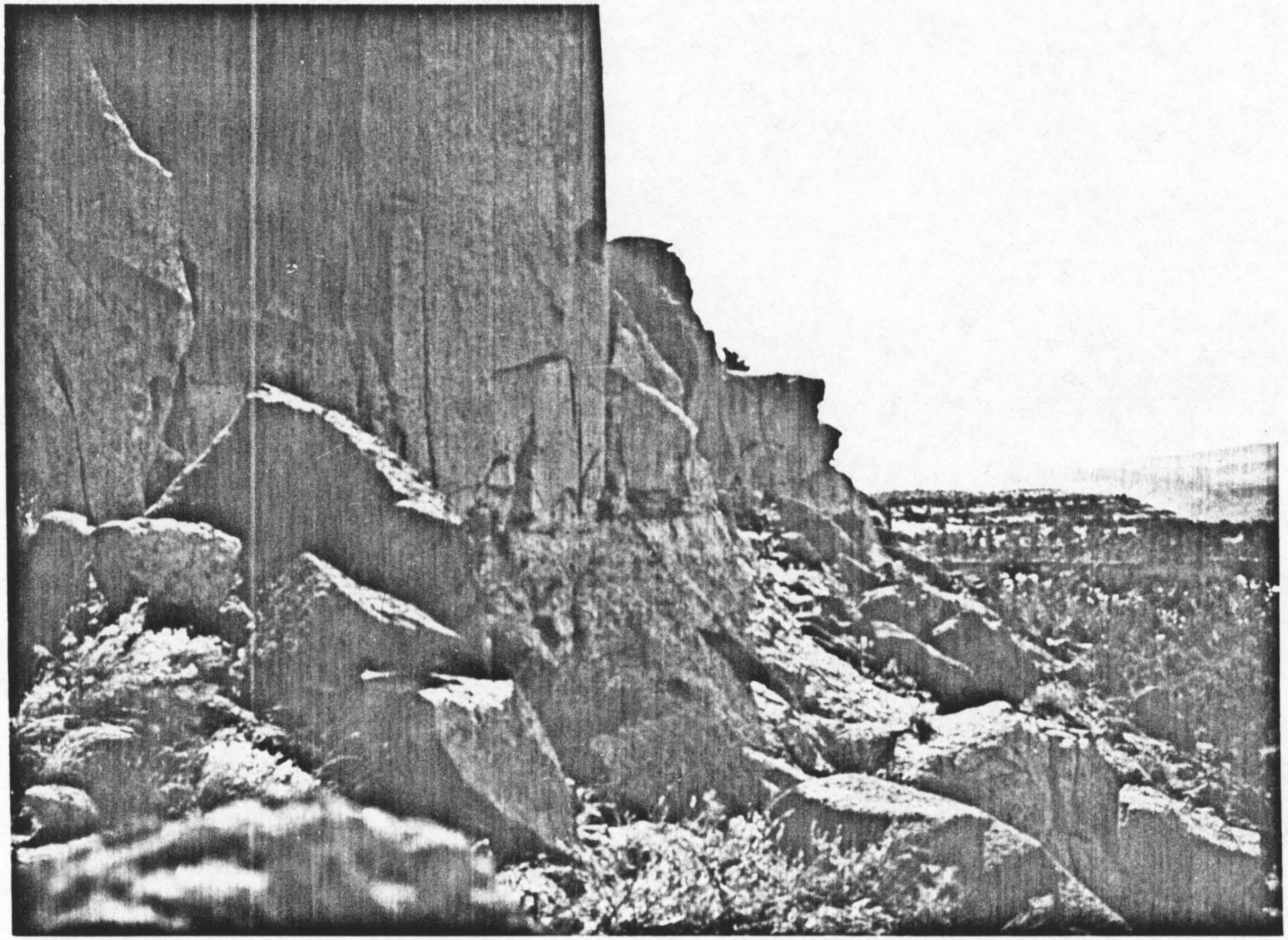

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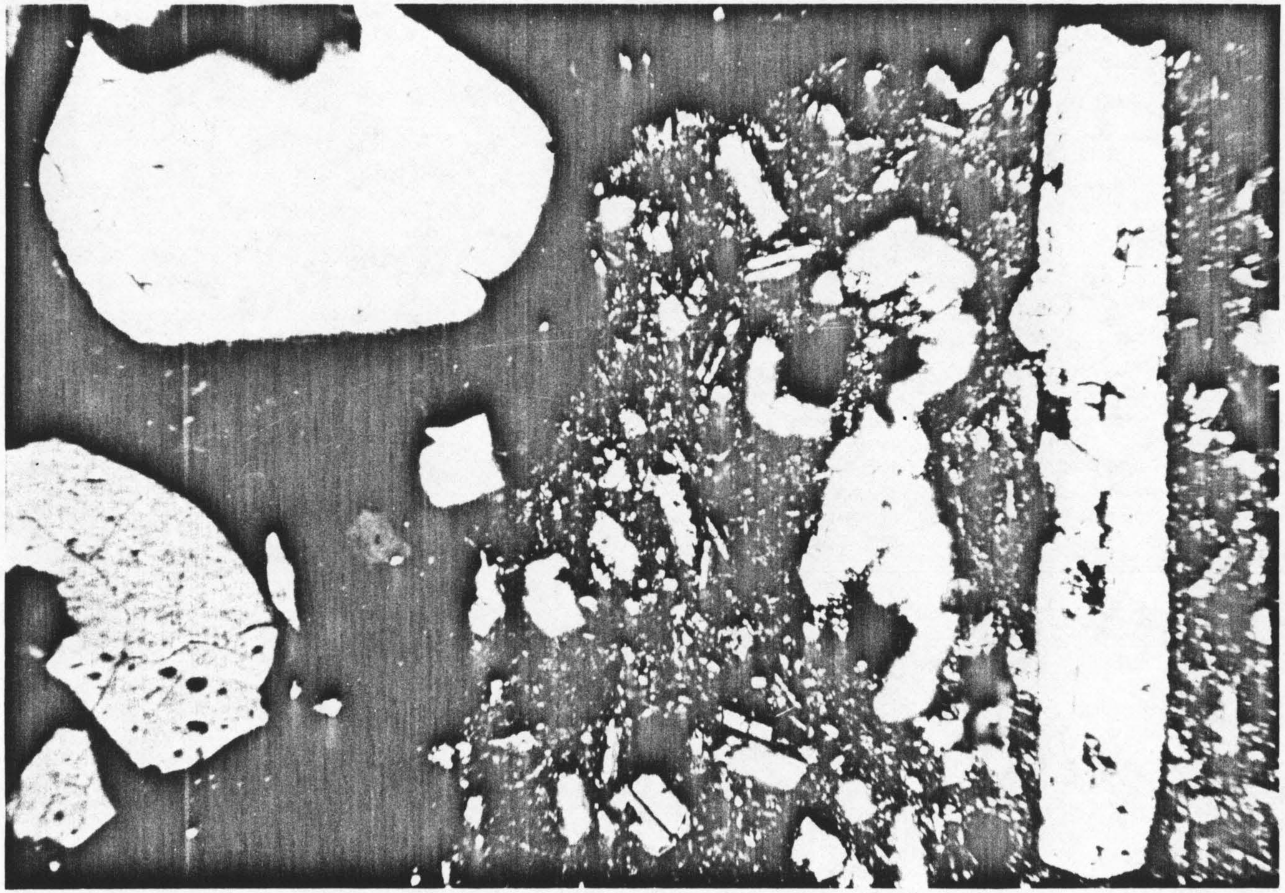

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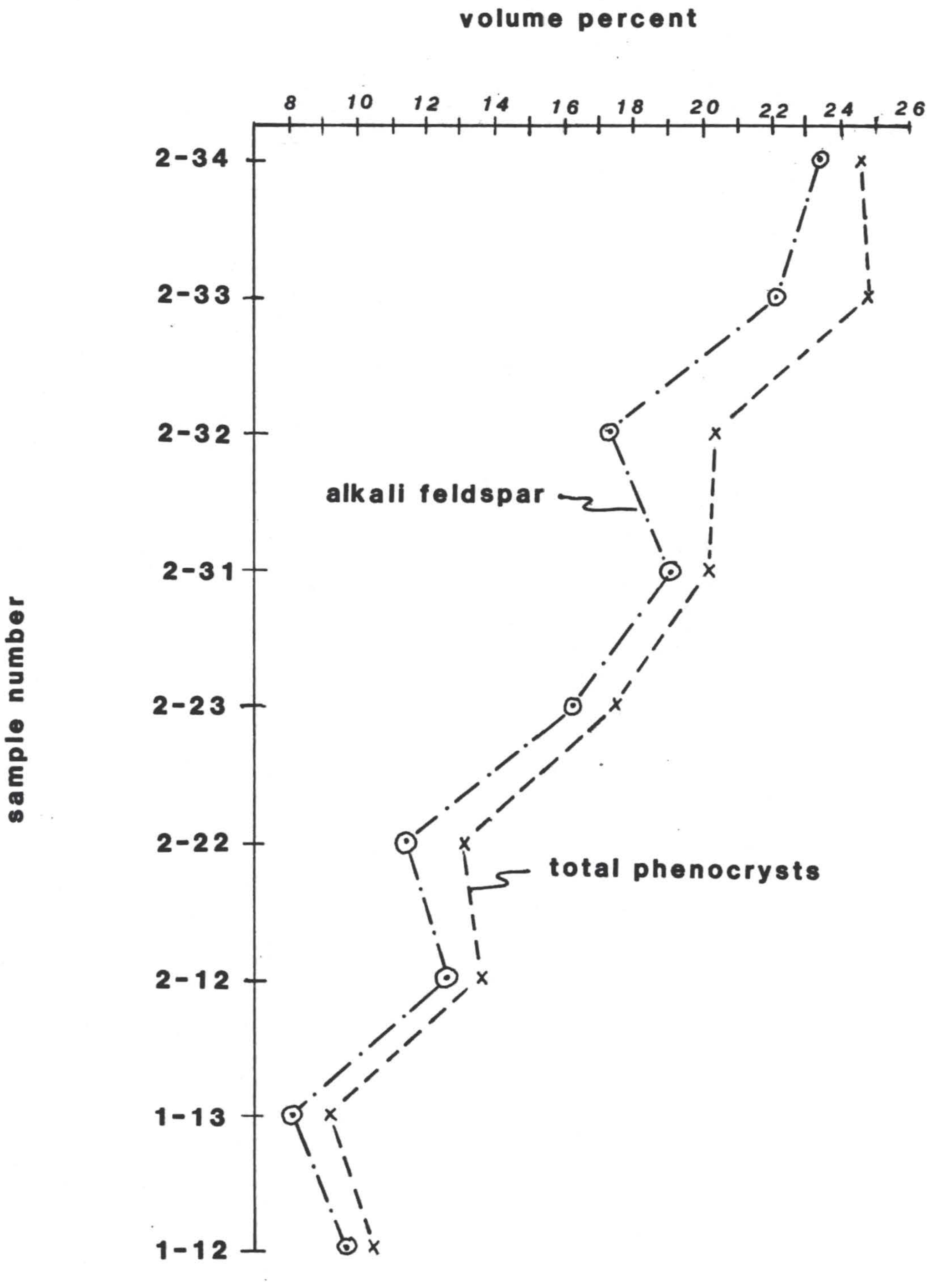
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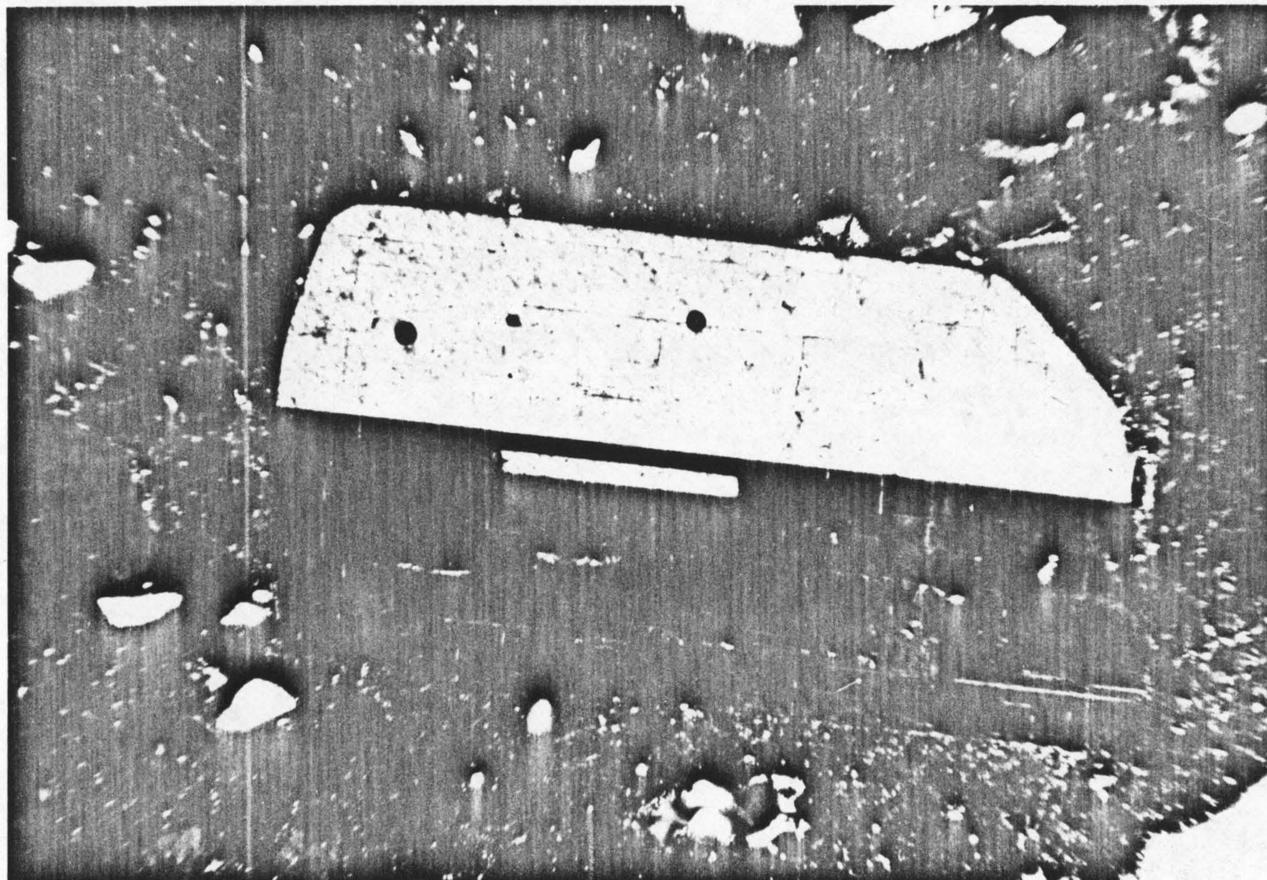
12
14
16
18
20
22
24
26
2-34
2-33
2-32
2-31
2-23
2-22
2-12
1-13
1-12
sample number
alkali feldspar
total phenocrysts

Figure 8



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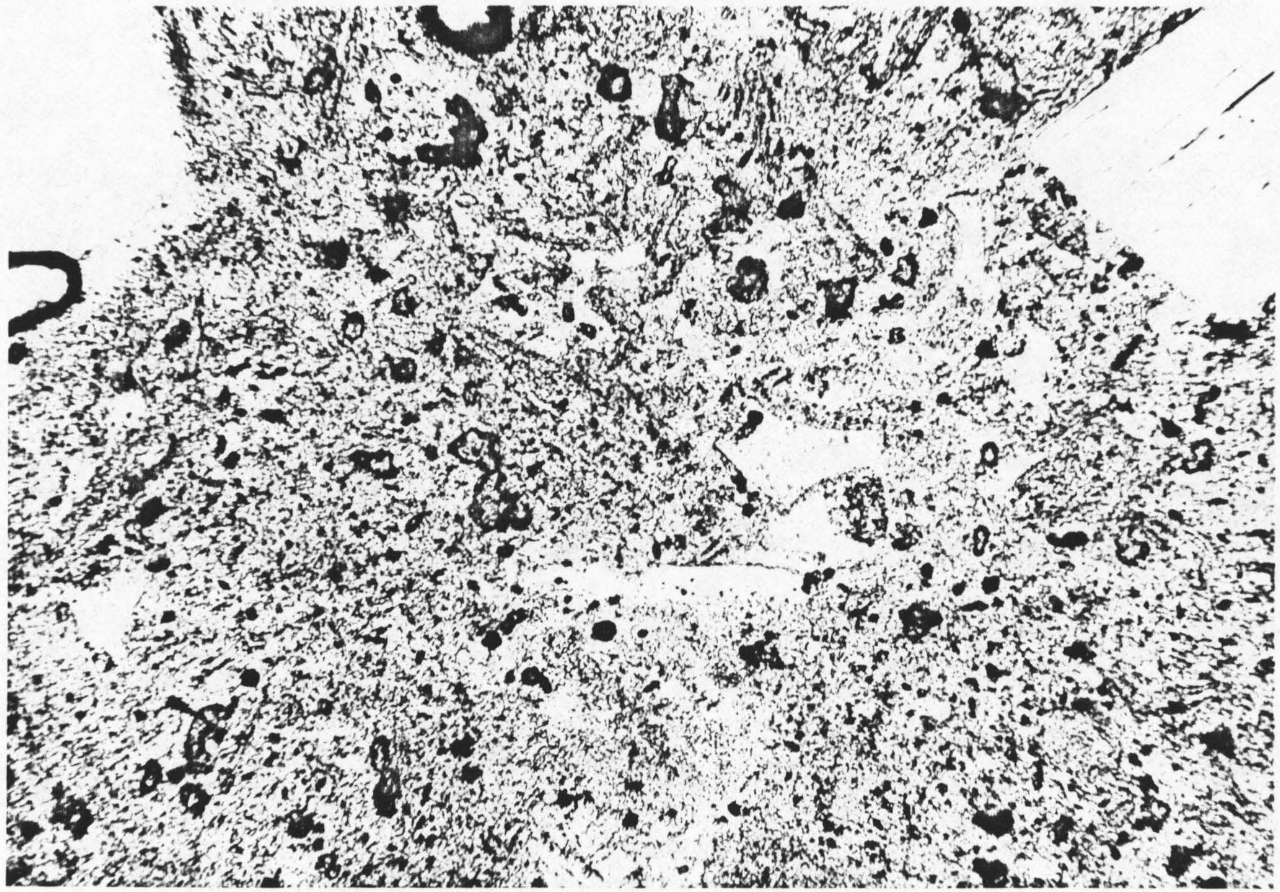

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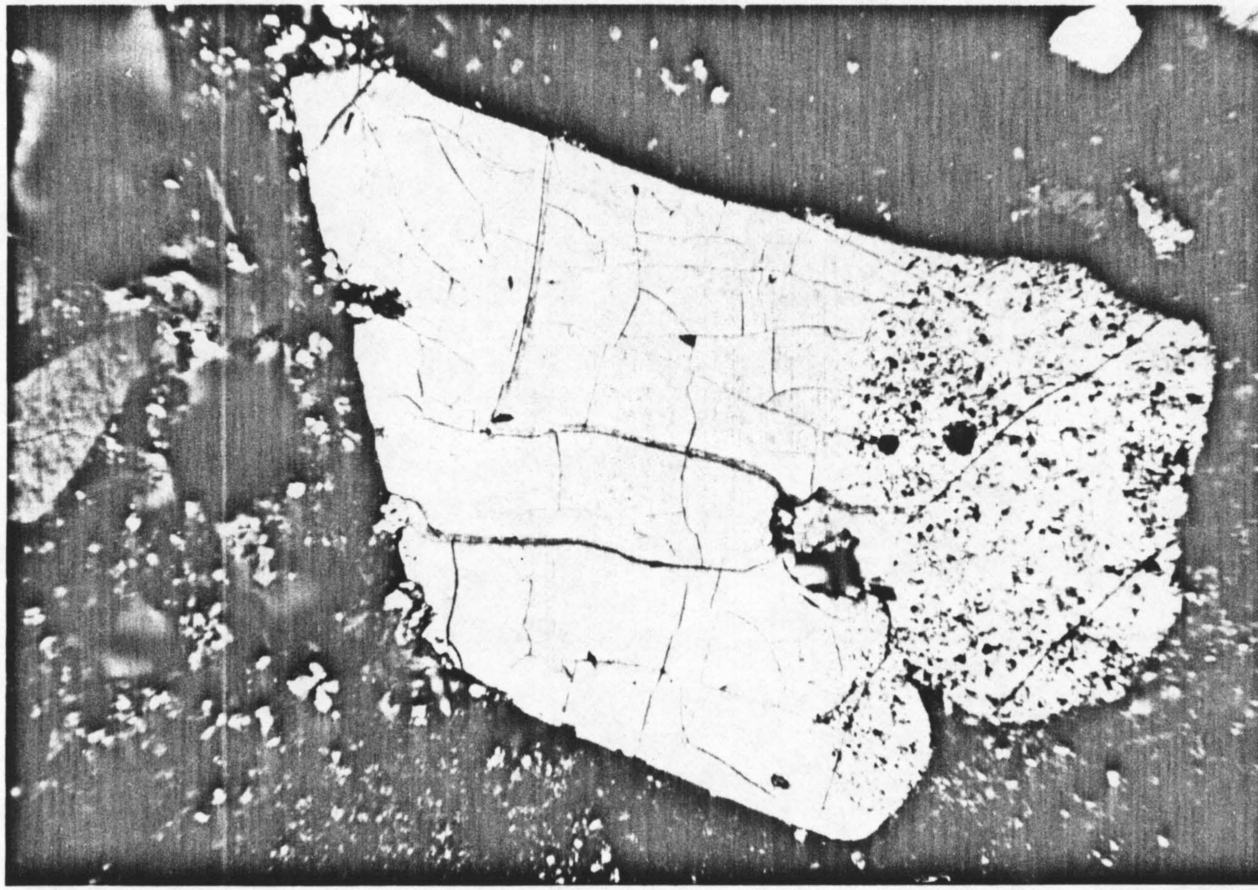

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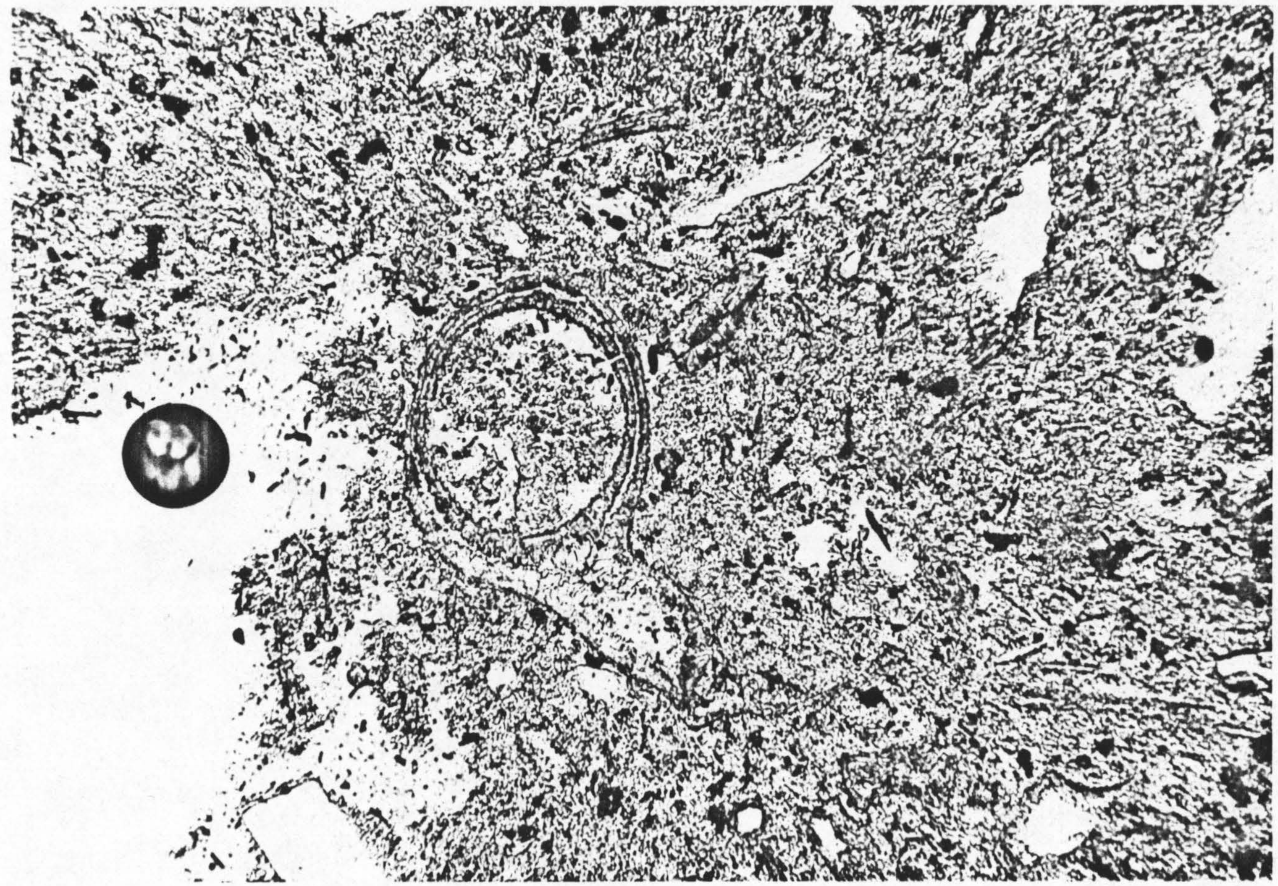

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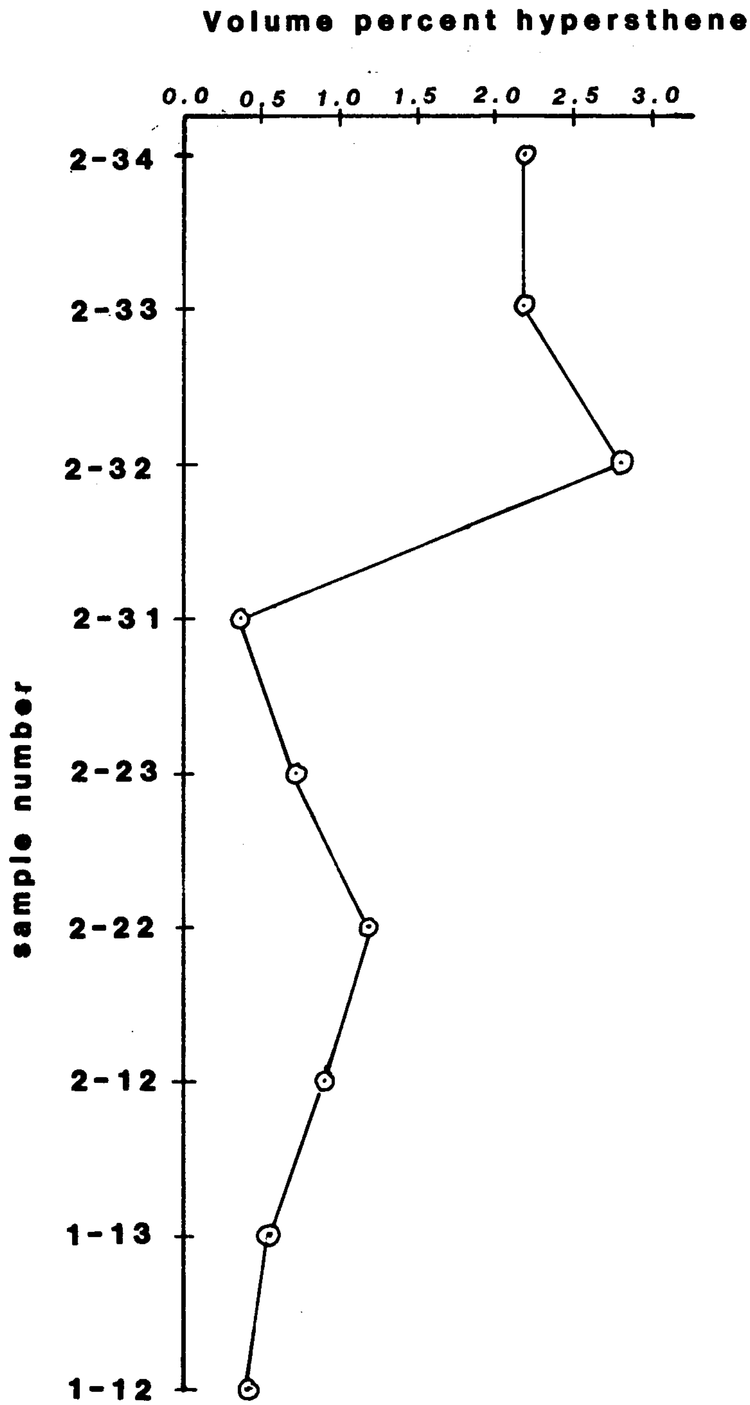
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1.0
1.5
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2.5
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2-34
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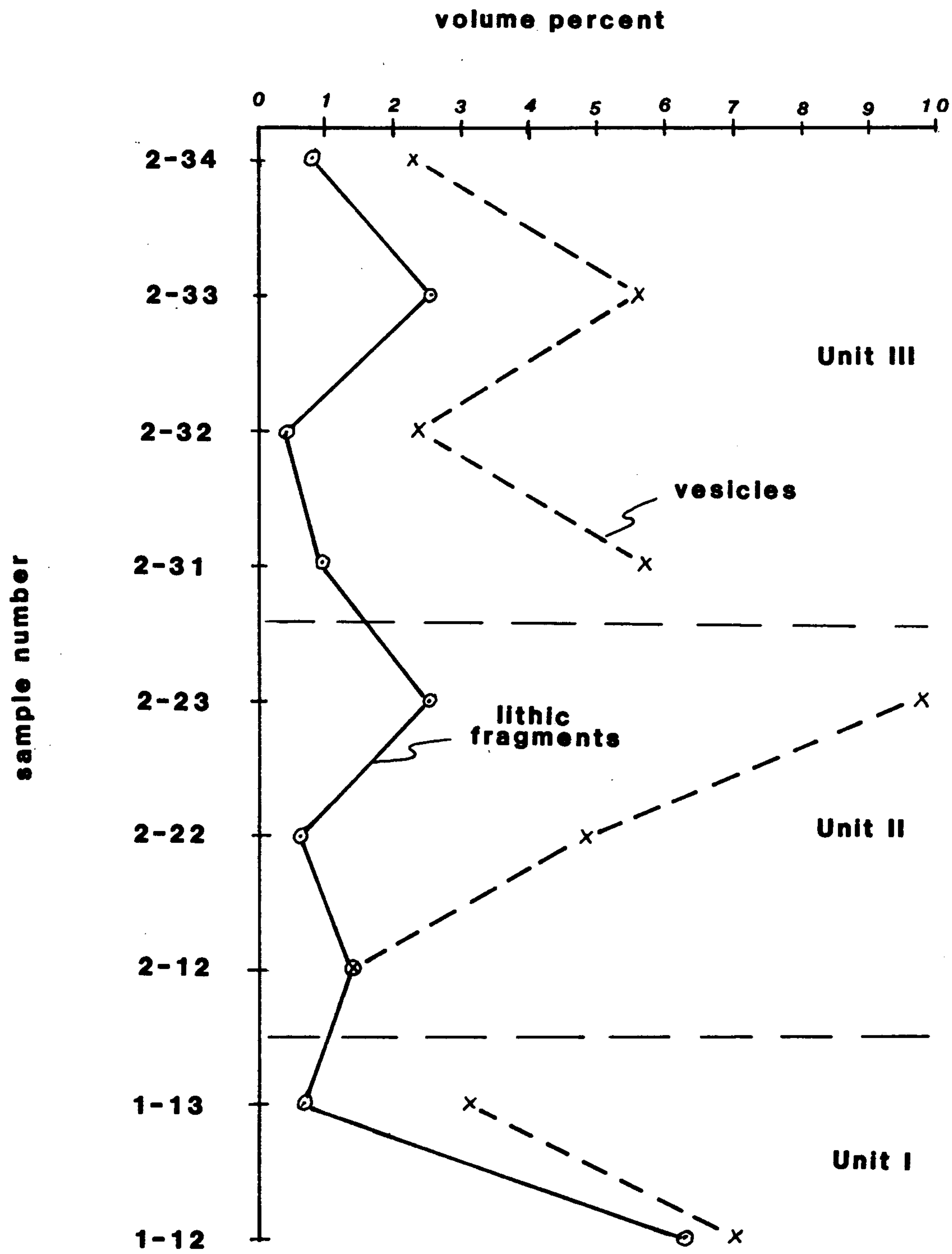
2-31
2-23
2-22
2-12
1-13
1-12

Figure 13


volume percent
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1
2
3
4
5
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7
8
9
10
sample number
2-34
2-33
2-32
2-31
2-23
2-22
2-12
1-13
1-12
Unit III
vesicles
lithic fragments
Unit II
Unit I

Figure 14

Table 1

SAMPLE #	ALKALI FELDSPAR	AMPHIBOLE	PYROXENE	OPAQUES	BIOTITE	PLAGIOCLASE	QUARTZ	LITHIC FRAGMENTS	VESICLES	PUMICE
2-34	X		X	X				X	X	X
2-33	X	X	X	X	X			X	X	X
2-32	X	X	X	X				X	X	X
2-23	X	X	X	X	X		X	X	X	X
2-22	X	X	X	X	X			X	X	X
2-12	X		X	X	X			X	X	X
1-13	X	X	X	X	X			X	X	X
1-12a	X	X	X	X	X	X		X	X	

Table 2

SAMPLE #	ALKALI FELDSPAR	AMPHIBOLE	OPAQUES	PYROXENES	VESICLES	LITHIC FRAGMENTS	GROUNDMASS
2-34	23.4	0.0	1.4	2.2	2.3	0.8	69.9
2-33	22.1	0.4	3.6	2.2	5.6	2.6	63.5
2-32	17.4	0.2	1.6	2.8	2.4	0.3	75.3
2-31	19.0	0.9	3.7	0.3	5.7	0.9	69.3
2-23	16.3	0.3	0.8	0.7	9.8	2.5	69.4
2-22	11.6	0.2	0.7	1.2	4.9	0.6	80.8
2-12	12.7	0.0	2.0	0.9	1.4	1.4	81.6
1-13	8.1	0.4	0.7	0.6	3.1	0.7	96.4
1-12a	9.7	0.3	1.4	0.4	7.0	6.3	74.7